Satellite Communications for Aeronautical Applications: Recent Research and Development Results

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ABSTRACT

Communications systems have always been a critical element in aviation. Until recently, nearly all communications between the ground and aircraft have been based on analog voice technology. But the future of global aviation requires a more sophisticated "information infrastructure" which not only provides more and better communications, but integrates the key information functions (communications, navigation and surveillance) into a modern, network-based infrastructure. Satellite communications will play an increasing role in providing information infrastructure solutions for aviation. Developing and adapting satellite communications technologies for aviation use is now receiving increased attention as the urgency to develop information infrastructure solutions grows. The NASA Glenn Research Center is actively involved in research and development activities for aeronautical satellite communications, with a key emphasis on air traffic management communications needs. This paper describes the recent results and status of NASA Glenn's research program.

INTRODUCTION

The future of aviation worldwide is one of significant continuing growth in air travel, air cargo, and private general aviation. In parallel with this growth, a significant increase in the supporting information infrastructure will need to occur. The infrastructure will support two primary functions: aviation operational needs (which includes airline operations, air traffic management/air traffic control, flight information services, and crew communications), and passenger services (internet connectivity, voice/data, travel services, etc.). This infrastructure must also enable radical new air traffic management methods, which require a large flow of information between the aircraft, air traffic service providers, and airline operations centers.

Passenger services communications are expected to generate revenue for airlines and service providers. They will require a "critical mass" of users to justify costly avionics installation and operating costs, hence they will need to be broadband services. They will therefore evolve in a market driven way, in fits and starts, with successes and failures dependent upon the quality and usefulness of service, customer acceptance, and service cost. While quality of service improves and costs are reduced, user demand for on-board communications connectivity will increase as the general public grows accustomed to ubiquitous access to wireless access in all other aspects

of life. Eventually the critical mass will be reached, broadband passenger services will become profitable, and broadband mobile connectivity to the majority of the commercial aviation fleet will be available.

Airline operational needs require major improvements to the communications infrastructure compared to the current system. The strain of increased air travel on the national and global aviation systems is resulting in increasing system congestion, whereby travelers experience growing delays and cancellations, and airlines suffer significant operating cost impact. To combat this growing congestion, radical new methods of managing air traffic are needed, as well as increased ground facilities (e.g., new runways and increased use of underutilized airports). Air traffic management and airline operations will become highly collaborative environments. Information such as aircraft location, speed, and flight plans must be provided rapidly and updated continuously. Weather and traffic information must be updated and distributed to all air traffic management entities. Brokering of arrival and departure times between airlines, prioritization of flights within airlines, and national and global traffic flow management will become standard procedures. An integrated digital information infrastructure is required to enable such an aviation system.

It is becoming recognized in the aviation industry that satellite communications will be required to provide the capacity and coverage necessary for a future aviation communications infrastructure. The current ground–based VHF communications channels will be unable to provide the required system capacity and coverage. For broadband satellite communications, higher frequency bands are be favored because they have more available spectrum and allow the use of much smaller antennas. Rain attenuation problems occurring at higher frequencies have low impact because most communications operations will occur above the rain. A hybrid communications architecture will emerge that includes both ground-based and space-based communications links, with the space-based links providing the majority of data transfer. In order to achieve minimum cost and foster widespread fleet equipage of satellite communications avionics, current communications functions and emerging communications functions must begin to share the available infrastructure. In other words, it will not be an option to continue to add more and more antennas and receivers and transmitters to aircraft. An integration of functions and communications links can result in a reduction of avionics installed on aircraft with greatly increased capability. This will require development of architectures and methods to insure the security, reliability and integrity of flight critical data in an integrated system that is simultaneously supplying full and open access for passenger services. To achieve this future integrated communications vision, much research, development and demonstration work must be completed.

The NASA Glenn Research Center is performing research and development in several key areas of satellite communications for aeronautical applications. This work includes the study of aviation communications system architectures and related network protocols in an aeronautical environment, research and development in some key aeronautical satellite communications technologies, and the evaluation and demonstration of satellite communications technologies for aeronautical applications. The purpose, status and recent results of NASA Glenn's work in aeronautical satellite communications is presented below.

FUTURE REQUIREMENTS FOR AERONAUTICAL COMMUNICATIONS

It is recognized that significant changes in air traffic management are required to allow the projected increases in the capacity of the US National Airspace System (NAS), as well as for other crowded airspace regions. The current method of nearly complete control of an aircraft's flight through commands from ground-based air traffic controllers cannot keep pace with air traffic growth, and results in system capacity constraints and less than optimum flight routes for aircraft. Under NASA's Advanced Air Transportation Technologies Project, new air traffic control methods are being researched. These methods rely on a greater automation of the airspace and collaboration between aircraft, air traffic service providers, and airline operations centers to increase efficiency and throughput. The concept is called Distributed Air/Ground Traffic Management and requires a significant amount of data sharing between the collaborating entities[1]. Up-to-date information on aircraft location, trajectory, speed and intent must be continuously updated and made available to both ground controllers and nearby aircraft, greatly increasing the air-to-air and air-to-ground communications load. "Negotiations" between aircraft to avoid potential future separation conflicts will further increase the air-to-air communications load. Traffic information services (TIS), which include the state of the NAS, neighboring aircraft within a given operational area, and flight information services (FIS), such as current weather and weather forecasts and airport conditions, are vital to efficient operations. TIS and FIS require increased ground-to-air communications. Improved surveillance and traffic control of surface vehicles at crowded airports will require local ground information infrastructures.

Passenger communications represent a significant and growing segment of aeronautical communications needs. In terms of pure bandwidth required, passenger communications will far outstrip all other aeronautical communications needs. It is estimated that over $US 3 billion in annual revenue can eventually be generated through passenger communications service fees[2]. Opportunities may exist to leverage the relatively high bandwidth passenger communications infrastructure to relieve the burden on narrowband communications frequencies used for safety critical function.

AERONAUTICAL COMMUNICATIONS SYSTEM ARCHITECTURES

The development of appropriate architectures for information infrastructures capable of efficiently handling the integrated CNS needs of the future is an on-going process. Recent studies and papers have emphasized the need for a hybrid approach that includes both ground-based communications links and satellite links[3,4]. Current aeronautical communications between the air and ground are primarily in the VHF band (118-137 MHz). Emerging digital communications links, called VHF Digital Link (VDL) will transition the VHF channels from analog voice to provide digital data and digital voice capabilities. VDL Mode 2, which provides digital data communications using a carrier sense multiple access technique, is in its initial stages of deployment. VDL Mode 3 will employ time division multiple access in order to obtain 4 communications sub channels within a VHF channel, providing both digital voice and data channels. Full deployment of VDL Mode 3 is not scheduled until after the end of the current decade. VDL Mode 4, which uses a self-organizing TDMA access technique and can provide aircraft-to-aircraft communications and is in development and early initial deployment in some regions. The VDL modes require a significant deployment of ground infrastructure – hundreds

of ground transmitters and receivers as well as thousands of radios. The installation of antennas and transceivers into commercial aircraft will ultimately cost hundreds of millions of $US. With such a large investment, it is easy to see why the VHF datalinks will remain in use for decades.

At the same time, it is questionable whether the VHF links, which can be used over only the limited VHF civil aeronautical band, can meet all of the future air traffic management needs. Many research issues remain outstanding in this area. Hence, hybrid information infrastructure architectures, which include satellite communications links as a key component, are being proposed. These architectures, previously described in [3,4], consider the addition of satellite communications links into an information network advantageous because of their inherent properties: economical wide-area broadcast capabilities, large scale geographic coverage including oceanic and remote regions, coverage of all altitudes, lower terrain blockage, and larger available bandwidth at the higher frequencies. Satellite navigation methods (utilizing augmented GPS and other global positioning systems) are a recognized part of future air navigation and air traffic management. Satellite-based surveillance is also being considered as a future air traffic management component.

NASA Glenn is currently pursuing research in information architectures, including the analysis of the performance capabilities of VDL and satellite communications links for air traffic management and FIS applications, and the evaluation of hybrid terrestrial-satellite network architectures. The development of component and system models is progressing and results of simulations, analyses and other research will be the subject of future reports.

DEVELOPMENT OF KEY TECHNOLOGIES

Recent studies commissioned by NASA Glenn[3,5,6] and experience gained during work on aeronautical communications research programs have indicated a number of technology developments needed to hasten implementation of satellite communications for aeronautical applications. Systems or component technologies needed for future aircraft information systems include high speed flight deck and cabin data network components, data servers, multifunction displays and intelligent routers. For VHF communications, directional and multifrequency VHF antennas, antennas and receivers with improved interference and adjacent channel rejection, and improved modulation techniques, compression and voice synthesis. For satellite communication systems, multi-mode radios, efficient modulation and carrier recovery techniques, improved receivers and antennas for Ka Band, improved antenna pointing and tracking algorithms, and the establishment of mobile standards are needed. Also needed are improved interfaces to NAS information databases and security techniques.

Given resource limitations, several of these technologies have been chosen for research and technology development within NASA's current programs. The technologies were selected based on their relative level of importance, available NASA Glenn technical expertise, and the availability of other research programs with which collaboration could be created. These technologies are Ku and Ka Band phased array antenna development; modulation and coding technology for aeronautical satellite communications links; high speed fiber optic signal distribution; and improved antenna pointing and tracking algorithms. These research and development efforts are described in the following paragraphs.

Ku and Ka Band Phased Array Antenna Development

NASA Glenn is participating in a program sponsored by the U.S. Navy's Space and Naval Warfare Systems Center to develop Ka Band ultra small aperture terminal (USAT) technology. The Boeing Company is developing key components for the USAT, including Ka Band phased array transmit and receive antennas. In addition to enhanced antenna RF performance, a key feature of this program is to develop a design with a high degree of manufacturability, eliminating or reducing by-hand manufacturing steps in order to produce low cost arrays. System level testing of prototype arrays is scheduled to begin in 2002.

In a prior development through the same program sponsor, NASA Glenn contributed significant resources toward the development of a Ku Band transmit phased array antenna, also produced by Boeing. The transmit phased array, and a companion receive phased array previously developed by Boeing, were designed for use on aircraft to access commercial Ku Band satellites currently in orbit. These two antennas form the basis of NASA Glenn's Ku-Band Mobile Aeronautical SatCom Terminal and Testbed, described below, and also are the basis for Boeing's Connexion by Boeing_SM airline passenger communications system.

Modulation and Coding Technology

NASA Glenn, Purdue University and Cleveland State University are performing research on improving the characteristics of aeronautical satellite communication links through improved modulation, coding, access techniques and signal processing. The key problems being addressed are data transmission performance; the need for faster recovery times when the signal is lost due to aircraft turns and banks that exceed the antenna scanning range; interference rejection; and link security. Purdue University researchers are studying adaptive matched filtering and adaptive signal processing techniques to reduce susceptibility to signal fading and mitigate interference and jamming. Researchers from Cleveland State University are studying the characteristics of signals recorded during testing of NASA Glenn's Ku-Band Mobile Aeronautical SatCom Terminal to quantify key properties of aeronautical satellite communications links. NASA Glenn will work with Purdue and Cleveland State with the goal of developing prototype modems for evaluation in the Mobile Terminal.

High Speed Fiber Optic Signal Distribution

NASA Glenn is developing a testbed to investigate signal distribution architectures that make use of wavelength division multiple access techniques to enable multiple signals, including both modulated RF and digital baseband signals to be transmitted over a single fiber. Such a system can be used to provide a very large bandwidth on-board network for an aircraft and can transmit many different signal types and connect different signal sources and users (antennas, receivers, transmitters, signal processing units, displays, passenger video units,
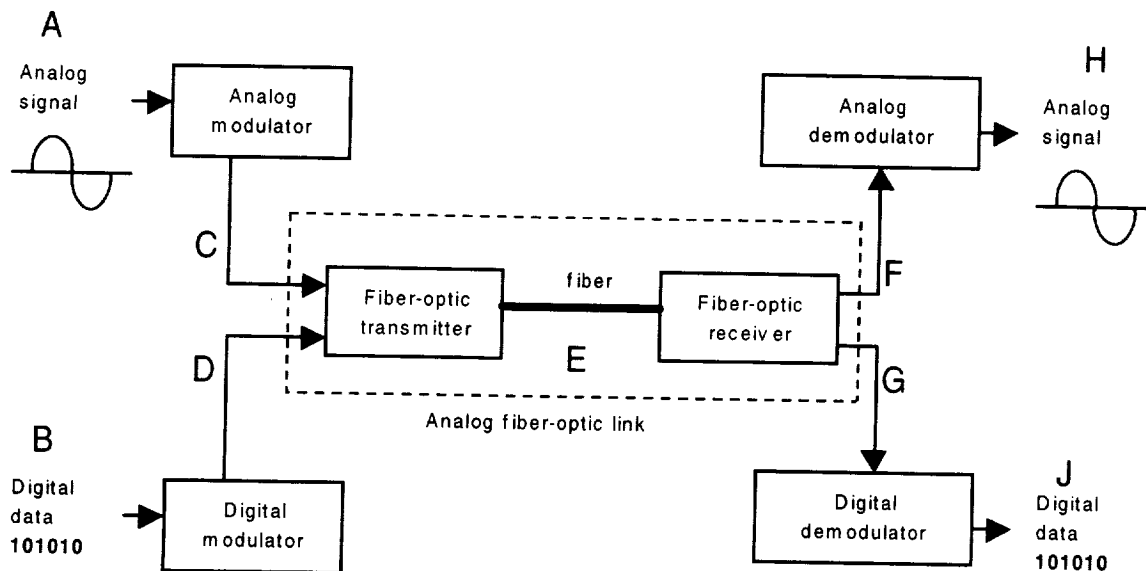
Figure 1 – Experimental setup for fiber optic signal distribution.

etc.). Other advantages are less signal loss, lower interference susceptibility and lower weight (compared to conventional twisted wire and coaxial cable). The testbed is being constructed at NASA Glenn and initial tests will investigate the capability of transmitting multiple signals over a single fiber and measure received signal quality in the presence of multiple signals propagating on the fiber. Figure 1 shows the initial laboratory setup.

Antenna Pointing and Tracking Algorithms

NASA Glenn is performing research in antenna pointing and tracking algorithms for managing the operation of phased array antennas for aeronautical satellite communications links. Operation of the Ku Band Mobile Aeronautical SatCom Terminal indicated that significant improvements in antenna pointing (acquiring the maximum satellite signal) and tracking (maintaining the maximum signal during flight maneuvering) were needed. This research is in its initial stages. NASA Glenn plans to implement improved antenna pointing and tracking algorithms in prototype form during late 2002.

KU-BAND MOBILE AERONAUTICAL SATCOM TERMINAL AND TESTBED

A key part of NASA's aeronautical communications research and development program is an evaluation/demonstration program of satellite communications for aeronautical applications. To meet this goal, NASA Glenn has developed the Ku-Band Mobile Aeronautical SatCom Terminal and Testbed. This terminal enables the testing and demonstration of satellite communications for aeronautical applications, the performance of various air traffic management, flight information service, and other related data applications over a satellite link, the integration of terrestrial and satellite communication links into a single network regime, and the performance of aeronautical satellite link components.

The terminal is based upon the Boeing-developed Ku Band phased array antennas described above. The Ku Band frequency was chosen as a frequency of opportunity for demonstrating aeronautical satellite communications concepts: the Ku Band receive phased array antenna already existed so only the transmit array needed to be developed; Ku Band commercial satellites are available with sufficient power and bandwidth; Ku-Band Mobile Aeronautical SatCom Terminal and Testbed; and Ku Band is a sufficiently high frequency to demonstrate the benefits of using higher satellite bands for aeronautical communications (e.g. antennas of sufficiently small size to be mounted on aircraft).
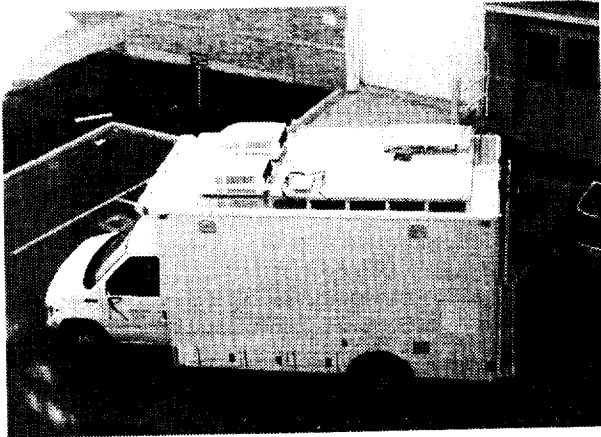

Figure 2 – Ku Band Mobile Aero-SatCom terminal mounted in the ground mobile van.

The terminal is capable of connecting to standard data sources and providing transmission and reception of data through any standard commercial Ku band satellite to and from any location within the satellite's coverage area. It is designed to be mounted either in a van for ground mobile experiments or in a NASA research aircraft for air mobile experiments. The ground mobile van, with transmit and receive phased array antennas mounted on top, is shown in Figure 2. In the ground mobile configuration, a gyro system is used to feed inertial navigation information to the antenna controller to enable antenna pointing to be maintained during mobile operations. For the air mobile configuration, the aircraft's inertial navigation system provides the navigation information for antenna pointing.

In conjunction with the aero mobile terminal, a laboratory testbed is being developed which will enable the creation of realistic test scenarios. The ground testbed will emulate a region of airspace, including the communications occurring between aircraft and ground, so that a ground mobile or air mobile test can be conducted within an air traffic setting adequate to test and demonstrate the performance of the mobile terminal in a system environment. The testbed will include an experiment communications network that can be used to test the performance of air traffic control algorithms that include a satellite communications link. This will provide important verification of the ability of satellite communication links to operate within a hybrid aeronautical communications network in a transparent fashion, and enable any real problems with such hybrid networks to be identified and addressed.

The first major flight test of the Aero-SatCom Terminal occurred in December 2000. The terminal was installed in NASA's DC-8 research aircraft, as shown in Fig. 3. During flight tests at altitudes up to 40,000 feet, successful operation of the aero-mobile terminal in a duplex communication mode was demonstrated. Internet network connectivity was established through a range of simultaneous applications including web browsing, e-mail, and voice-over-IP. Tests of Aeronautical Telecommunications Network (ATN) applications and Remote Buffered Net3work Bus (a network configuration designed for distribution of research data from the aircraft including prioritization and security features) were also successful. Live video and DC-8 Digital Air Data system data were transmitted. Transmit data rates (from the aircraft to the fixed

earth station at NASA Glenn) of 256 kbps and receive data rates (from NASA Glenn to the aircraft) of 2.180 Mbps were achieved.
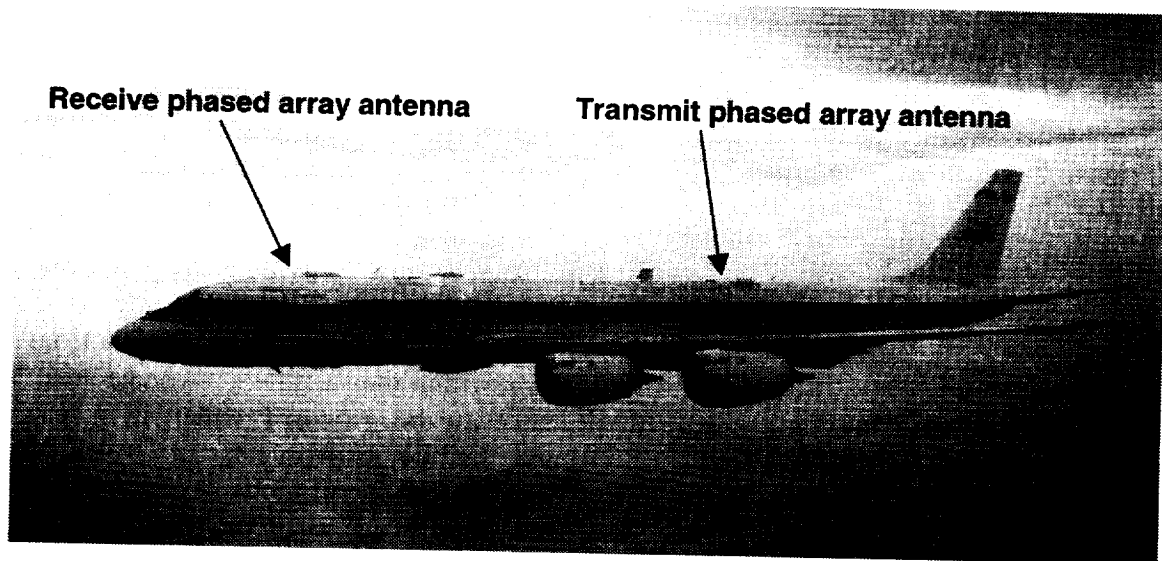

Figure 3 – Recent flight tests of NASA Glenn's Ku Band Aeronautical Satellite Communications Terminal on the NASA DC-8 (December, 2000).

Recent tests of the ground mobile terminal configuration resulted in quantitative performance measurements. In transmission tests between the NASA Glenn fixed Ku Band earth station and the mobile van (during mobile operations) bit error rates of zero were maintained while supporting data rates of 256 kbps (from mobile to fixed station) and 2.048 Mbps (from fixed station to mobile). These data rates were limited by the modems used in the experiments. The measured carrier-to-noise ratios indicated E_b/N_o in the range of 15 to 17 dB, yielding approximately 6 dB of link margin. Hence, both forward and reverse data rates could be doubled while still maintaining a comfortable margin.

Experiments and demonstrations of the Ku Band Aero-SatCom Terminal will continue through 2004, with several additional flight tests on NASA's 757 research aircraft stationed at the Langley Research Center planned. As the experiments progress, the emphasis will shift to more complex network oriented experiments to evaluate and demonstrate air traffic management and FIS applications in a hybrid terrestrial/satellite network environment

CONCLUSIONS

To enable increased capacity of the national and global airspace systems, much greater amounts of information must be transferred among various entities within the system. An information infrastructure in which modern networked communications enable the movement of navigation, surveillance, air traffic management, operations, and other information, as well as providing passenger communications, with capabilities far beyond the current infrastructure, is a vital necessity. Satellite communications will be an important part of that infrastructure. Research

and development activities at NASA's Glenn research Center are focused on advancing key satellite communications technologies for aeronautical uses so that these technologies can be implemented as soon as possible. Several key technologies and research areas are being pursued, including advanced modulation, coding and signal processing; high frequency phased array antennas; improved antenna pointing and tracking algorithms; high speed fiber-optic signal distribution; modeling and simulation of terrestrial and satellite communication links; and analysis of communications and information infrastructure architectures. NASA Glenn has also developed a Ku Band Mobile Aeronautical Satellite Communications Terminal and Testbed for evaluating and demonstrating these technologies. This terminal has provided the first demonstrations of the ability for satellite communications to provide complex network connectivity suitable for the aeronautical communications environment.

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